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ANALYSIS OF RAIL WEAR AND PREDICTION OF SERVICE LIFE AT THE FATMAWATI CURVE OF MRT JAKARTA

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Abstract

Urban mass transit systems, such as the Jakarta Mass Rapid Transit (MRT) support high mobility but face track maintenance challenges from rapid degradation. Rail wear is the gradual loss of material due to repeated wheel rail contact while the contributing factors include friction, forces, accumulated passing tonnage, environmental conditions, material quality, and lack of lubrication. The Fatmawati Curve, characterized by a sharp 180-meter radius, exhibits one of the highest wear rates along the MRT Jakarta line due to intense dynamic forces. This study comprehensively analyzes the rail wear rate and its contributing factors at this critical location, while predicting the remaining rail service life using Simple Linear Regression and the theoretical AREA (American Railway Engineering Association) method. Empirical data were obtained from precise measurements conducted by the Civil Permanent Way Maintenance (CPWM) team of PT MRT Jakarta from May 2024 to June 2025 on both the Up Track and Down Track. The analysis results indicate that horizontal wear is the dominant degradation mechanism on this curve, progressing significantly and exceeding 5 mm after 84 months of operation, while vertical wear remains minimal at below 1.5 mm. Based on the maximum wear limits stipulated by national regulations (Permenhub No. 32/2011), the Simple Linear Regression model estimates that the critical wear limit will be reached between 2029 for the Down Track and 2030 for the Up Track. In contrast, the AREA method provides a longer, theoretical service life estimation extending to 2035 because it primarily accounts for material fatigue limits rather than physical field wear. Because the linear regression projections more accurately reflect actual aggressive field conditions, proactive track maintenance interventions such as optimized track lubrication, geometric control, and scheduled rail replacement at the Fatmawati Curve are highly recommended prior to 2029 to prevent technical failures and ensure long-term operational safety.

Keywords*: Rail Wear, Service Life Prediction, Linear Regression, AREA Method, MRT*

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INTRODUCTION

Jakarta, as the nation's capital and the primary economic hub in Indonesia, faces significant challenges regarding rapid population growth. This demographic surge directly implicates high daily mobility, which, if not managed effectively, leads to chronic traffic congestion and diminished urban efficiency [1]. As a strategic solution to untangle these transportation issues, the government developed a mass, efficient, and sustainable public transportation system: the Jakarta Mass Rapid Transit (MRT) [2]. Since commencing commercial operations in 2019, Jakarta MRT Phase 1, connecting Lebak Bulus to Bundaran HI, has become the backbone of urban transport, serving thousands of passengers daily [2].

The operational reliability of Jakarta MRT is heavily dependent on the prime condition of the railway infrastructure. A railway track is not merely a path; it is a complex structure consisting of steel and concrete components designed to support heavy train loads and guide movement safely [3]. Given the high axle loads and dense trip frequencies, rail components constantly undergo mechanical interaction with train wheels. This interaction, occurring repeatedly over long periods, leads to material degradation in the form of wear [4]. The phenomenon of wear becomes particularly critical on track sections with curved geometries.

In curved tracks, especially those with small radii such as the Fatmawati Curve on the Jakarta MRT line, an uneven load distribution occurs between the wheels and the rails. The centrifugal force generated as the train passes causes the wheels to press more strongly against the outer rail, increasing contact pressure and lateral friction [5]. This triggers an accelerated rate of wear, both vertical wear and horizontal wear [5]. If the wear level exceeds the tolerance limits stipulated in national safety standards, such as those regulated by Minister of Transportation Regulation Number 60 of 2012, the risk of technical failures like derailment increases significantly [6]. Therefore, periodic monitoring and analysis of rail wear is a crucial aspect of railway infrastructure maintenance management.

Several previous studies have attempted to examine the issue of rail wear from various perspectives. S. A. Yudistirani et.al, [7] conducted an analysis of wear and derailment safety factors for locomotive trains, but the study did not link wear data to future rail service life predictions. They also studied the relationship between rail wear and wheel stability, concluding that routine monitoring is essential to maintain travel safety. Specifically, regarding the Jakarta MRT location, research by Amin and Prayogi [8] discussed the influence of corrugation on the Fatmawati curve but did not comprehensively compare field findings with the target design service life of the rails. There remains a research gap where in-depth analysis is needed that combines actual field measurement data with statistical modeling to predict the remaining service life of rails, particularly on MRT lines with unique operational characteristics.

As a solution to these problems, this study offers a comprehensive analysis of the rail wear rate on the Fatmawati Curve of the Jakarta MRT using high-precision measuring tools, namely the RIFTEK Rail Profile Measurement System and the Rail Wear Measurement Gauge [12]. Data obtained from actual measurements on the Up Track and Down Track are analyzed to determine vertical and horizontal wear values. Furthermore, this research applies a linear regression analysis method using SPSS software to model the relationship between accumulated tonnage of passing loads and the resulting wear levels [11],[13]. The results of this modeling are used to predict when the rail will reach its maximum wear limit in accordance with the standards of Minister of Transportation Regulation Number 32 of 2011 [10]. By knowing the predicted service life of the rails, the Jakarta MRT management can formulate more proactive maintenance schedules, such as rail grinding or lubrication, to extend the technical life of the rails and optimize operational costs [9], [10]. Through this approach, the research is expected to provide a tangible contribution to enhancing the safety standards and efficiency of mass transportation systems in Indonesia.

LITERATURE REVIEW

Rail Wear

Rail wear involves profile changes or dimensional reduction of the rail head. This phenomenon is primarily caused by repeated mechanical interactions between train wheels and the rail surface [1]. The process is heavily influenced by contact forces, friction, and dynamic loads transmitted through the wheels. Wear is generally classified into two main types: vertical wear on the top surface of the rail head, and horizontal wear on its inner side [6]. On curved tracks, significant lateral forces push the wheel flange against the outer rail, causing horizontal wear to occur faster and more dominantly than vertical wear [5].

Rail Wear Standards in Indonesia

The Indonesian government has established strict rail wear tolerance limits to ensure railway safety. Specifically, Minister of Transportation Regulation No. 60/2012 mandates the material and geometric specifications for main line rails R56. Furthermore, Minister of Transportation Regulation No. 32/2011 outlines infrastructure maintenance standards, specifying the maximum limits for vertical wear (*a*) and horizontal wear (*e*) based on the rail type, as shown in Table 1 [10]. Rails exceeding these limits are declared unfit for service and require immediate replacement (rail renewal) to prevent derailment risks [6].

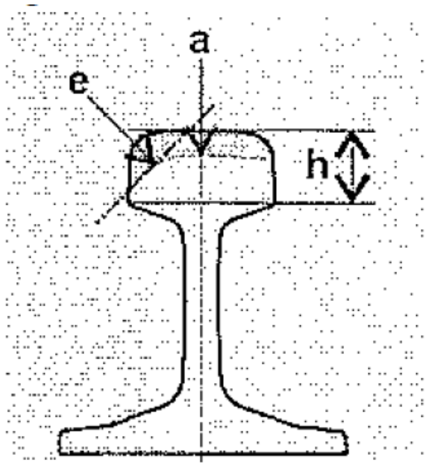

Figure 1. Rail Wear

Table 1. Maximum Rail Wear Limit

Type of Rail	**e.$_{max}$ (mm)**	**a.$_{max}$ (mm)**
R42	13	10
R50	15	12
R54	15	12
R60	15	12

Railway Track Geometry on Curves

Railway geometry is designed to ensure safe, comfortable, and efficient train movements. On non-tangent tracks, geometry is classified into horizontal and vertical curves [1], [3]. A horizontal curve accommodates track direction changes, parameterized by its radius, central angle, and length. Superelevation (cant) is applied in these curves to counteract centrifugal forces [5]. Conversely, a vertical curve connects track segments with different gradients, preventing sudden slope changes to maintain stable compressive or tensile forces on the train [1].

Rail Service Life Prediction

Rail service life prediction estimates the remaining time or accumulated load a rail can endure before reaching its maximum wear limit. A common approach correlates the wear rate with the accumulated tonnage of passing loads, typically measured in Million Gross Tons (MGT) [4]. Linear regression models are frequently utilized in this analysis to observe wear trends as the load increases [4]. However, previous literature has not sufficiently addressed rail service life prediction by integrating actual field measurement data with robust statistical modeling, highlighting a critical gap in current infrastructure maintenance studies.

RESEARCH METHODOLOGY

Research Procedure

This study adopts a descriptive quantitative approach to analyze the rail wear rate and reliably predict its remaining service life. The research procedure is conducted systematically through four main stages. The first stage involves problem identification at the Fatmawati Curve and a comprehensive literature review regarding national railway safety standards (Minister of Transportation Regulation No. 32/2011 and No. 60/2012). The second stage is field data acquisition, where actual geometric profiles of the rails are measured using laser instrumentation. The third stage encompasses data processing, where the raw profile data is converted into vertical and horizontal wear rates. Finally, the fourth stage involves statistical and theoretical data analysis, utilizing both the Simple Linear Regression model to project field-based service life and the AREA method to provide a theoretical benchmark for material fatigue.

Study Area and Data Collection

The primary location for data collection in this study is the Fatmawati Curve of the Jakarta Mass Rapid Transit (MRT) Phase 1 line. This specific location was selected due to its critical geometric characteristic, possessing a sharp curve with a radius of 180 meters. Data was gathered from both operational tracks: the Up Track (Lebak Bulus to Bundaran HI) and the Down Track (Bundaran HI to Lebak Bulus) between KM 2+441 and KM 2+760. The rails evaluated in this study are R54 type rails that were officially installed and commenced operation in June 2018.

To ensure high precision and accuracy in capturing the material degradation, the field measurement was conducted using the RIFTEK Rail Profile Measurement System. This tool utilizes advanced laser scanning technology to capture the exact cross-sectional profile of the rail head non-destructively. The physical measurements were systematically carried out by the Civil Permanent Way Maintenance (CPWM) team of PT MRT Jakarta. The data collection period spans from May 2024 to June 2025, providing multiple data points to observe the progressive wear behavior over time. The obtained profile data was then extracted to determine the exact vertical and horizontal dimensional reduction of the outer rail (high rail) in millimeters.

Wear Rate Calculation

The wear rate is calculated to determine material degradation per unit of time (month) using the formula:

$$i = \frac{t_0 - t_1}{M} \tag{1}$$

Where:
i = wear rate (mm/month)
t_0 = Initial wear value (mm)
t_1 = Current wear value (mm)
M = Time interval between measurements (months)
$t_0 - t_1$ = Wear (mm)

Simple Linear Regression Model

This statistical approach utilizes the Ordinary Least Squares (OLS) method within the SPSS software environment to find the best-fitting straight line through the observed data points. In this context, the independent variable (X) represents the continuous operational time in months, while the dependent variable (Y) represents the cumulative horizontal wear in millimeters. By calculating the intercept (a) and the slope (b), the model generates a constant rate of degradation reflecting actual field conditions. To predict the remaining service life, the maximum allowable horizontal wear threshold mandated by Indonesian regulations—which is 15 mm for R54 rails—is substituted into the dependent variable (Y). The equation is then mathematically isolated to solve for (X), which yields the exact future month and year when the rail will become unfit for service and require immediate renewal:

$$Y = a + bX \tag{2}$$

Where:
Y = Predicted wear value (mm)
a = Intercept constant
b = Regression coefficient (slope)
X = Rail operational age (months)

AREA Method (American Railway Engineering Association)

The AREA method serves as a baseline to understand the maximum structural endurance of the steel material under ideal theoretical conditions. The calculation relies heavily on several operational parameters. The rail weight parameter (*W*) must be converted from the metric system (*kg/m*) to the imperial system (*lb/yard*) to fit the empirical formula. Furthermore, the track condition constant (*K*) is a crucial multiplier that accounts for the specific track environment. It is derived by multiplying the factor for Continuous Welded Rail (*CWR*) with the specific factor for track curves and lubrication. Meanwhile, the annual traffic density (*D*) represents the accumulated heavy loads passing over the rails per year, calculated based on train frequency, passenger load, and carriage weight. Once the total tonnage limit (*T*) is acquired, the predicted rail age (*U*) is simply determined by dividing the maximum tonnage capacity by the annual traffic density:

$$W = \frac{Rail\ weight\ (kg/m)}{0{,}496} \tag{3}$$

$$T = K \cdot W \cdot D^{0{,}565} \tag{4}$$

$$U = \frac{T}{D} \tag{5}$$

Where:
T = Total tonnage (Million Gross Tons (MGT))

K = Track condition constant
W = Rail weight (lb/yard)
D = Annual traffic density (MGT/year), 1 MGT = 909.000 ton
U = Rail Age (year)

RESULTS AND DISCUSSION

Rail Wear Inspection Results

Rail wear inspections were conducted at the Fatmawati Curve (180-meter radius) using the RIFTEK Rail Profile Measurement System [12]. Data was collected along both the Up Track (Lebak Bulus – Bundaran HI) and the Down Track (Bundaran HI – Lebak Bulus) between KM 2+441 and KM 2+760. The analyzed rails were initially installed in June 2018. Table 2 presents the average accumulated wear and the calculated wear rate on the outer rail (high rail) for both operational tracks from May 2024 to June 2025. The wear rate (*i*) is determined by dividing the total dimensional reduction (t_0 - t_1) by the rail's operational duration in months (*M*).

Table 2. Rail Wear Data from May 2024 – June 2025

Track	Measurement Time	Duration M(month)	Avg. Vertical Wear (mm)	Rate i_{vert} (mm/month)	Avg. Horizontal Wear (mm)	i_{horiz} (mm/month)
Up Track	June 2018	0	0	0	0	0
	May 2024	71	0.52	0.007	3.14	0.044
	November 2024	77	0,68	0.009	3.84	0.050
	June 2025	84	1,43	0.017	5.29	0.063
Down Track	June 2018	0	0	0	0	0
	May 2024	71	0.47	0.007	2.58	0.036
	November 2024	77	0.84	0.011	4.05	0.053
	June 2025	84	1.18	0.014	5.13	0.061

As clearly shown in Table 2, the progression of horizontal wear is significantly more aggressive than that of vertical wear. For instance, by June 2025 (84 months of operation), the Up Track experienced 5.29 mm of horizontal wear compared to only 1.43 mm of vertical wear. This significant difference is a natural and expected phenomenon on track sections with sharp curves, such as the 180-meter radius at the Fatmawati Curve. When a train navigates this curve, the centrifugal force naturally pushes the train outward. As a result, the train wheels press forcefully against the inner side of the outer rail (high rail) to keep the train guided along the curved path. This continuous lateral interaction generates high friction and strong lateral forces, which significantly accelerate the material removal process on the side of the rail head. Because this horizontal degradation clearly dominates the overall rail deterioration at this location and will reach the safety threshold much faster than vertical wear, it becomes the primary concern for track maintenance. Therefore, only the horizontal wear data is utilized for the subsequent linear regression service life predictions, as it represents the most critical operational limit for passenger safety.

Simple Linear Regression Modelling and Service Life Prediction

Simple linear regression models the relationship between rail operational age (*X*, in months) as the independent variable and accumulated horizontal wear (*Y*, in mm) as the dependent variable. This model estimates when the rail wear will reach the maximum allowable limits set by the Minister of Transportation Regulation No. 32/2011. The data was processed using the Ordinary Least Squares (OLS) method in SPSS software [13].

The data processing to obtain the regression equation was conducted using SPSS software through the following steps [13]:

- Variable Definition: In the Variable View window, define variable X (Rail Age) and variable Y (Horizontal Wear).
- Data Input: Enter the research data into the corresponding columns in the Data View window.
- Command Navigation: Select Analyze → Regression → Linear from the main menu bar.
- Variable Assignment: Assign variable X to the Independent box and variable Y to the Dependent box.
- Execution: Click OK to process the data and generate the simple linear regression output.

Based on data processing using the ordinary least squares (OLS) method, two distinct equations were obtained for each operational track:

- Up Track $Y = -8{,}844 + 0{,}167X$
- Down Track $Y = -11{,}064 + 0{,}194X$

These coefficients indicate a steady horizontal wear progression over time, with the Down Track experiencing a significantly higher increasing wear rate up to 0.194 mm/month compared to the Up Track.

The service life prediction is calculated by substituting the 15 mm maximum horizontal wear threshold for R54 rails (Minister of Transportation Regulation No. 32/2011) as variable Y. Isolating variable X yields the predicted operational time remaining before replacement is strictly required:

- Up Track

$$15 = -8{,}844 + 0{,}167X$$
$$23{,}844 = 0{,}167X$$
$$X = 142{,}77\ months$$

Calculated from the initial installation in June 2018, the Up Track is predicted to reach the 15 mm limit by the 142nd month, or approximately April 2030.

- Down Track

$$15 = -11{,}064 + 0{,}194X$$
$$26{,}064 = 0{,}194X$$
$$X = 134{,}35\ months$$

The Down Track degrades faster and will reach the critical limit by the 134th month, approximately in August 2029.

Rail Service Life Prediction Using the AREA Method

The AREA (American Railway Engineering Association) method estimates the total accumulated tonnage (Million Gross Tons, or MGT) a rail can withstand before reaching its fatigue limit. This theoretical approach is based on material characteristics and traffic density, which is then compared against the actual field wear data. The parameters used in this calculation are derived from the R54 rail specifications and Jakarta MRT operational records:

- Rail Weight (*W*): The rail weight is 109.74 lb/yard, which is converted from the R54 specification of 54.43 kg/m. Using equation (3) for the calculation:

$$W = \frac{Rail\, weight(kg/\mathrm{m})}{0{,}496}$$

$$W = \frac{54,43}{0{,}496} = 108{,}87\ lb/yard$$

- Track Condition Constant (*K*): A constant of 0.52 is applied. This is the product of the Continuous Welded Rail (CWR) factor (1.39) and the curve lubrication factor (0.37)
- Annual Traffic Density (*D*): Based on operational records, the average annual traffic density is 14,8 MGT/year which id equivalent to 13,45 million ton/year

By applying the AREA empirical equation (4), the following results were obtained:

$$T = K \cdot W \cdot D^{0{,}565}$$

$$T = 0{,}5 \cdot 108{,}87 \cdot 14{,}8^{0{,}565} = 233{,}77\ MGT$$

233.77 MGT is treated as 233.77 million tons for operational calculation purposes.

To calculate the rail service life using the AREA method, equation (5) is used:

$$U = \frac{T}{D}$$

$$U = \frac{233{,}77\ million\ ton}{13{,}45\ million\ ton/year} = 17{,}4\ years\ or\ 17\ years\ 4\ months$$

A lifespan of 17.38 years equates to approximately 17 years and 4 months. Calculated from the initial installation in June 2018, the AREA method predicts that the Jakarta MRT rails at the Fatmawati Curve will remain serviceable until late 2035.

A comparative analysis reveals a distinct difference between the two predictive models. The linear regression method projects a remaining service life until 2029–2030, as it accurately captures the aggressive, physical wear dynamics occurring on the curved track. Conversely, the AREA method projects a much longer lifespan extending to 2035 because it relies strictly on theoretical material fatigue limits. Notably, both predictions significantly exceed the Jakarta MRT's conservative 5-year operational design life for 180-meter curved tracks. This extended service life validates the effectiveness of current maintenance programs, particularly the implementation of guard rails, water-based lubrication systems, and periodic rail profile grinding.

CONCLUSION

Based on the comprehensive analysis of rail wear and service life prediction at the Fatmawati Curve of the Jakarta MRT, several key conclusions and implications are drawn:

1. Data collected from May 2024 to June 2025 reveals distinct degradation patterns. Horizontal wear is significant, progressing at a steady rate of 0.063 mm/month and exceeding 5 mm after 84 months of operation. In contrast, vertical wear remains minimal at less than 1.5 mm. Because horizontal wear on this small-radius curve develops much

faster, it serves as the primary governing factor for determining the remaining rail service life.

2. The linear regression analysis projects that the rails will reach their maximum wear limit by 2029 for the Down Track and 2030 for the Up Track. These statistical projections are more representative of field conditions and current maintenance effectiveness. Conversely, the AREA method provides a longer prediction extending to 2035, which relies on a purely theoretical approach and may underestimate the aggressive dynamic forces acting on the curve.
3. These findings highlight the urgent need for targeted, proactive maintenance at the Fatmawati Curve prior to 2029. To extend the rail service life, it is crucial to increase the frequency of track inspections as wear approaches threshold limits. Furthermore, maintaining strict control over superelevation and track gauge widening is essential. Optimizing track lubrication systems will also significantly reduce friction rates and mitigate severe wheel-rail interaction, thereby protecting both the permanent way infrastructure and the rolling stock components.
4. From a policy perspective, this study emphasizes the necessity for transport authorities to update maintenance protocols, demonstrating that regulations must incorporate continuous calibration against actual field degradation data rather than relying solely on theoretical design lives. Academically, this research contributes to the broader field of railway mechanics and machine dynamics by providing a robust, evidence-based framework for future studies focusing on vehicle-track dynamics and predictive maintenance strategies.

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